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Natural Rail Hazards – Detection Technology Evaluation

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NATURAL RAIL HAZARDS – DETECTION TECHNOLOGY EVALUATION

By
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December 2004

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

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16 Abstract

This report details the work done for a review of natural hazard detection technologies relevant to railway rights of way. The main objective of this review was to provide the railway industry with a critical assessment of available or potential real-time track hazard detection technologies together with the tools to critique future technologies. Work focused primarily on those technologies identified at the Kananaskis Workshop on Slide and Washout Hazards (see Transport Canada publication TP 14053).

A review of the workshop literature and current developments in the geotechnical field was performed, and a number of promising technologies were investigated. A matrix was developed and 26 identified technologies were ranked; issues such as technology maturity, potential and applicability were addressed.

As a result of the review, two highly ranked technologies, ground-based radar interferometry and fibre-optic sensing, were selected for a more critical evaluation. The evaluation concluded that, while both systems offer significant advantages, neither represents the optimal solution. While it is unlikely that any single technology will satisfy all the requirements of hazard detection, both represent viable solutions in specific circumstances and their further development should be supported.

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16 Résumé

Ce rapport rend compte des travaux effectués dans le cadre d'une revue des technologies de détection des risques naturels pouvant menacer les emprises ferroviaires. L'objectif principal de cette revue était de fournir à l'industrie du transport ferroviaire une évaluation critique des techniques existantes ou potentielles qui peuvent être utilisées pour détecter en temps réel les risques que peuvent poser les voies ferrées, de même que les outils pour évaluer les futures technologies. Les travaux ont surtout porté sur les technologies dont il avait été question à l'Atelier sur les risques de glissement de terrain et de ravinement, tenu à Kananaskis (voir la publication
TP 14053 de Transports Canada).

Après un examen du compte rendu de l'atelier et des développements en cours dans le domaine de la géotechnique, un certain nombre de technologies prometteuses ont été scrutées plus avant. Une matrice a alors été confectionnée pour le classement de 26 technologies selon différents critères, comme la maturité, le potentiel et l'applicabilité.

Ensuite, deux des technologies qui se sont classées parmi les premières, soit l'interférométrie radar terrestre et les fibres optiques, ont été retenues pour une évaluation approfondie. Cette évaluation a mené à la conclusion que les deux technologies offrent des avantages considérables, mais que ni l'une ni l'autre ne représente une solution optimale. Alors, même s'il est peu probable qu'une de ces technologies puisse à elle seule répondre à toutes les exigences en matière de détection des risques, toutes deux peuvent représenter des solutions viables selon les circonstances, et il convient de soutenir leur développement.

17 Mots clés	18 Diffusion
Gestion du risque, géotechnique, fibres optiques, interférométrie radar terrestre, InSAR, chemin de fer, risque géologique, temps réel, glissement de terrain, éboulement, ravinement, érosion, avalanche, classement	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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EXECUTIVE SUMMARY

The main objective of this review was to provide the railway industry with a critical assessment of available or potential real-time track hazard detection technologies together with the tools to critique future technologies as they are developed. This project dealt primarily with those technologies identified at the Kananaskis Workshop on Slide and Washout Hazards (see Transport Canada publication TP 14053).

In the first part of the review the technologies identified were entered into a ranking matrix (interactive Excel© spreadsheet) according to identified priorities, the most important of which was real-time capability. A total of 26 technologies were identified and ranked. Issues such as technology maturity, potential and applicability were addressed.

In the second part of the review, two highly ranked technologies, ground-based radar interferometry and fibre optics, were selected for a more critical evaluation. The evaluation was done at a level consistent with a pre-feasibility level program. The main goal was to evaluate the different technologies on a per rail metre (i.e., the alignment along the length of the railway track) baseline according to their ability to satisfy specific requirements. A proposal from the fibre-optic technology company is also presented.

SOMMAIRE

L'objectif principal de ce projet était de fournir à l'industrie du transport ferroviaire une évaluation critique des techniques existantes ou potentielles permettant de détecter en temps réel les risques que peuvent poser les voies ferrées, de même que les outils pour évaluer les futures technologies au cours de leur développement. Les travaux ont surtout porté sur les technologies dont il avait été question à l'Atelier sur les risques de glissement de terrain et de ravinement, tenu à Kananaskis (voir la publication TP 14053 de Transports Canada).

Dans un premier temps, les technologies recensées ont été portées sur une matrice de classement (tableur Excel© interactif) en fonction de priorités choisies, la plus importante étant la capacité de signaler les événements en temps réel. Au total, 26 technologies ont été recensées et classées. Les critères pris en compte comprenaient la maturité de la technologie, son potentiel et son applicabilité.

Dans un deuxième temps, deux des technologies qui se sont classées parmi les premières, soit l'interférométrie radar terrestre et les fibres optiques, ont été retenues pour une évaluation approfondie. Le niveau de cette évaluation correspondait à celui d'une étude de pré-faisabilité. Le but principal était d'évaluer les différentes technologies sur la base d'un mètre de rail (c.-à-d. d'une longueur dans l'axe de la voie ferrée), selon leur capacité à répondre à des exigences précises. Une proposition concernant la technologie des fibres optiques et des renseignements sur le fournisseur de cette technologie sont aussi présentés.

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1 INTRODUCTION

Canada's harsh environments and broad expanse render its national railway industry particularly vulnerable to natural hazards. Primarily, these take the form of slides or washouts with the potential for significant, detrimental economical, social and environmental consequences. To mitigate the deleterious impact of such events, the industry has undertaken a number of initiatives aimed at enhanced management of natural risks.

One such initiative was the May 2002 workshop on landslide and washout hazards in Kananaskis, Alberta, under the sponsorship of various federal government agencies, the Railway Association of Canada, Canadian National Railway, Canadian Pacific Railway and VIA Rail (see Transport Canada publication TP 14053). While the workshop participants were successful in identifying industry needs, applicable technologies and potential avenues to pursue in enhancing risk management, they also recognized that real value will only result from concrete and timely action by the stakeholders.

Since risk management is heavily dependent on information (i.e., intelligently processed data), a critical component is the acquisition of pertinent and sufficient data from hazard detection technologies. MIRARCO's Geomechanics Research Centre was subcontracted by the University of Alberta's Department of Civil and Environmental Engineering to undertake a review of natural hazard detection technologies relevant to railway rights of way. This report summarizes the work executed under this subcontract.

2 TECHNOLOGY RANKING

In the first part of the review, the technologies identified were entered into a ranking matrix (interactive Excel© spreadsheet) according to identified priorities, the most important of which was real-time capability. The technologies were primarily those identified by the work groups during the "Workshop on Slide and Washout Hazards, Managing Natural Risks on Railways" (MNRR) in Kananaskis, Alberta, in May 2002.

The matrix is composed of five distinct categories:

1. Hazard;
2. Real-time detection/warning;
3. Availability;
4. Coverage; and
5. Function.

Each category contains at least two sub-categories allowing for the development of a binary ranking schema within each category. The binary ranking consists of either a positive value "X" signifying that the criterion has been met, or a null value signifying that it has not. This schema allows for only one positive value per category, except for in the first and last categories as noted below, and was adopted to eliminate the subjectivity inherent in the selection of a numerical value within a prescribed range (i.e., evaluator bias).

2.1 Hazard

The Hazard category refers to the type of event to be detected. Five were selected based on those identified in MNRR:

1. Slides: Failure of adjacent uphill or downhill slope (or both) resulting in a service disruption (e.g. track obstruction).
2. Washout: Failure of the ballast and culvert to resist dynamic flooding forces at a stream/river crossing, resulting in a complete washout of either all or a combination of the ballast, sub-ballast, sub-grade (platform) and natural ground, resulting in a service disruption. Failure can also occur as a result of animal habitat (e.g. flooding due to a beaver dam).
3. Erosion: Failure of either all or a combination of the ballast, sub-ballast, sub-grade (platform), and natural ground to resist dynamic forces (e.g. stream/river that lies parallel to the track, or wind). Failure can also occur as a result of animal habitat (e.g. erosion due to beaver dam breach).
4. Rockfall: Fallout debris, cobble size or larger (dia. $\geq$ 30 cm), from adjacent uphill rock slopes, causing obstruction of track (e.g. rail and/or fastening system).
5. Avalanche: Slide debris from adjacent snow-covered slope, causing obstruction of the track.

2.2 Real-Time Capability

The Real-Time Detection/Warning category refers to the capability of the technology to identify the hazard concurrent with its manifestation. Classification is denoted as:

1. Yes: Indicates that the technology can perform the required computation during the actual time that the related physical process occurs, for all applicable hazards, and that these results can then be used in conjunction with a detection or warning system. The system data can also be accessed remotely (e.g. off-site).
2. Near: Indicates that while the detection technology itself may be real-time, it is not always on-line; its availability is system dependent (e.g. aircraft-mounted measurement systems). Results are available either while the system operates or shortly thereafter (e.g. the plane flies over the subject area and then the data is downloaded). The system may not provide remote access to data.
3. Upgrade: Indicates that while the system normally requires intervention to obtain data (e.g. download from data loggers on a regular basis), with additional investment, the technology can be upgraded to near real-time or real-time on a case-by-case basis.
4. No: Indicates that the technology is not real-time and cannot be upgraded without significant investment.

2.3 Availability

The Availability category refers to the market readiness of the technology. This category is sub-divided into *Future* and *Current*. The former indicates that the technology is still in the research stage (not yet ready for commercialization) and the latter indicates ready availability in the open market via one or more commercial distributors.

2.4 Coverage

Coverage refers to the areal extent of monitoring capability. This category is divided according to size (i.e., footprint). *Micro* indicates that the technology can monitor only a localized area (or multiple small areas; e.g. within 1 km track length); *Macro* indicates a capability of continuously monitoring a wide area/length of track (on the order of kilometres).

2.5 Function

Function refers to the primary purpose of the data provided by the technology. Classification is either *Measurement,* indicating that the output obtained is a quantitative value yielding an unambiguous determination, or *Indicator,* signifying a qualitative output (i.e., an indication of hazard susceptibility) requiring additional investigation to confirm. The classification can be hazard dependent.

2.6 Ranking

The ranking of any technology represents its cumulative score relative to that of alternate technologies. The score is determined as the numerical sum of the score in each of the five categories.

To enable some measure of transparent bias to be introduced to the ranking, the user can select the three categories of most importance (Priority Weighting: 4, 3 & 2). Those not selected as one of the top three carry a weighting of 1. In addition, Importance Weightings (Very High to Low) must be applied to each sub-category. This allows for a weighting value to be applied to each positive binary selection, "X". Consequently, the score in any category is the product of the positive binary value "X" (equal to 1), the Priority Weighting and the Importance Weighting.

$$\text{Score} = X * \text{Priority} * \text{Importance}$$

Application of the above weightings to the technologies identified at MNRR resulted in the rankings presented in Table 1.

Table 1 Natural rail hazard detection technology rankings

		1	2				3		4		5		
		Hazard	Real time detection/warning				Availability		Coverage		Function		
			FIRST				SECOND		THIRD				
			VERY HIGH	HIGH	MEDIUM	LOW	LOW	HIGH	HIGH	LOW	LOW	MEDIUM	SCORE
			Yes	Near	Upgrade	No	Future	Market	Macro	Micro	Indicator	Measurement	
1	Interferometric Radar (ground based)	Slides X			X			X	X		X	X	31
		Washout X											
		Erosion X											
		Rockfall X											
		Avalanche X											
2	Fibre optics	Slides X	X					X	X		X		36
		Washout X											
		Erosion											
		Rockfall X											
		Avalanche X											
3	Real-time radar & API radar (colour coded)	Slides X	X					X		X	X	X	35
		Washout X											
		Erosion X											
		Rockfall X											
		Avalanche X											
4	Digital video imagery analysis	Slides		X				X		X	X		25
		Washout											
		Erosion											
		Rockfall X											
		Avalanche											
5	Time Domain Reflectometry (TDR)	Slides X	X					X		X		X	31
		Washout X											
		Erosion											
		Rockfall											
		Avalanche											
6	Siesmic Trigger (Micro Seismic, CANMET)	Slides	X					X		X			28
		Washout											
		Erosion											
		Rockfall X											
		Avalanche											
7	InSAR, Satellite	Slides X				X		X	X		X	X	27
		Washout X											
		Erosion X											
		Rockfall X											
		Avalanche X											
8	UAV (unmanned aerial vehicles)	Slides X		X				X	X		X	X	35
		Washout X											
		Erosion X											
		Rockfall X											
		Avalanche X											
9	Electro level beam detector	Slides X		X				X		X		X	30
		Washout X											
		Erosion X											
		Rockfall X											
		Avalanche X											
10	Total station system (site specific target scheme)	Slides X		X				X		X		X	30
		Washout X											
		Erosion X											
		Rockfall X											
		Avalanche X											

Table 1 continued...

		1	2				3		4		5		
		Hazard	Real time detection/warning				Availability		Coverage		Function		
			FIRST				SECOND		THIRD				
			VERY HIGH	HIGH	MEDIUM	LOW	LOW	HIGH	HIGH	LOW	LOW	MEDIUM	
			Yes	Near	Upgrade	No	Future	Market	Macro	Micro	Indicator	Measurement	SCORE
11	Permanent GPS installation	Slides X Washout Erosion X Rockfall Avalanche X		X				X		X		X	28
12	Electromagnetic field disturbance detection (co-axial cable)	Slides X Washout X Erosion Rockfall X Avalanche X		X				X		X		X	29
13	Track Monitoring Detector (e.g. Mile 9 Dundas Sub)	Slides Washout X Erosion X Rockfall Avalanche			X							X	12
14	Photo electric sensor (Photo Electric Erosion Pins, PEEP)	Slides Washout X Erosion X Rockfall Avalanche			X			X		X		X	23
15	Conventional Geotechnical Instrumentation	Slides X Washout X Erosion Rockfall X Avalanche			X			X		X	X	X	25
16	Water level detector	Slides X Washout X Erosion X Rockfall X Avalanche			X			X		X	X		24
17	Stationary Sensors	Slides X Washout X Erosion X Rockfall X Avalanche X			X			X		X		X	26
18	Snow Pack Surveillance & Avalanch Monitoring Systems	Slides Washout Erosion Rockfall Avalanche X			X			X	X		X		25
19	Ground Penetrating Radar (GPR)	Slides Washout X Erosion Rockfall Avalanche			X			X	X			X	26
20	Georeferenced assisted video inspection (spring geohazard heli-patrol, and beaver dam monitoring)	Slides X Washout X Erosion X Rockfall X Avalanche X				X		X	X		X	X	27

Table 1 continued...

		1	2				3		4		5		
		Hazard	Real time detection/warning				Availability		Coverage		Function		
			FIRST				SECOND		THIRD				
			VERY HIGH	HIGH	MEDIUM	LOW	LOW	HIGH	HIGH	LOW	LOW	MEDIUM	
			Yes	Near	Upgrade	No	Future	Market	Macro	Micro	Indicator	Measurement	SCORE
21	CYCLOP-3D (Landslide monitoring with Multidate georeferences images, aircraft)	Slides X Washout Erosion Rockfall Avalanche				X		X	X		X		21
22	Slide fence	Slides X Washout Erosion Rockfall Avalanche				X		X		X		X	18
23	Slump washout detector	Slides Washout X Erosion Rockfall Avalanche				X		X		X		X	18
24	Re-settable rockfall detectors	Slides Washout Erosion Rockfall Avalanche					X						3
25	Robotic/advance automated inspection ahead of train	Slides Washout Erosion Rockfall Avalanche					X						3
26	Roadbed integrity warning system	Slides Washout Erosion Rockfall Avalanche					X						3

3 TECHNOLOGY EVALUATION

In the second part of this review, two highly ranked technologies, ground-based radar interferometry (GB-InSAR) and fibre optics, were selected for a more critical evaluation. It should be noted that the score for the radar has been reduced from that reported earlier due to a downgrading of its real-time detection capability. Provider X was identified as a proponent of radar interferometry, while an Australian company, Future Fibre Technologies Pty. Ltd. (FFT), was identified as the leading developer of relevant fibre-optic sensing technology.

The evaluation was done at a level consistent with a pre-feasibility level program. The main goal was to evaluate the different technologies on a per rail metre (i.e., the alignment along the length of the rail track) baseline according to their ability to satisfy specific requirements.

3.1 Evaluation Criteria

The criteria by which the technologies were evaluated included:

1. Operation: Functionality in good, poor, and extreme weather conditions (the latter corresponds to a probability of occurrence less than 0.01)
2. Resolution: Derailment obstruction (small object ~ 0.028 m^3) detection capability
3. Creep detection: Capability to resolve slow movement rates
4. Output: Field and range limitations, false trigger susceptibility, automatic/remote reset capability, transmission requirements
5. Robustness: Ability to withstand maintenance zone operations, if located therein, as well as overall system ruggedness
6. Cost: Capital and operating per rail metre under surveillance
7. Vandalism: System susceptibility in both urban and remote locales

3.2 Reporting

Both Provider X and FFT submitted reports according to a prescribed format to facilitate evaluation and comparison. A copy of FFT's submission is attached in Appendix A. These reports were reviewed and supplemented by personal communication. A summary of the information provided is presented in Table 2.

Table 2 Technology comparison

Criterion	GB-InSAR	Secure Pipe™
Description	The technology is based on the principles of Synthetic Aperture Radar (SAR) and interferometry. SAR images (containing information on both signal amplitude and phase at each pixel) are generated by moving the radar antenna along a linear track. As the radar platform tracks along an identical path for each image, any phase difference at a pixel in time-separated images can be directly related to ground motion along the radar line-of-sight, provided the dielectric properties of the observed area have remained unchanged.	The technology is based on a photonic interferometer. A laser provides a light source that is equally divided to follow two fibre guided paths. The two beams are then recombined to mix coherently and form a "fringe pattern", which is directly related to the optical phase difference between them; the phase difference results from any disturbance experienced by the light over its transmission path.
Current Application	The Joint Research Centre (JRC) of the European Commission has built four ground-based systems (denoted LISA) differing only in linear track length. These have been primarily employed in technology validation studies but are now seeing application in monitoring mass movements for civil protection. A recent paper describing the current state-of-the-art is included in Appendix B.	FFT has installed four trial units globally that have yielded positive results. These trials involved a variety of sensor lengths, cable types and soil conditions. The basic technologies and physical principles used in Secure Pipe™ are the same as employed in FFT's Secure Fence™ products, which are used by major industry and government agencies.
Operation	Fixed station relatively immune to weather severity, with the exception of power/data transmission infrastructure. However, heavy precipitation (snow or rain) can attenuate the radar signal and thus impair performance.	Insensitive to weather conditions, with the exception of sensing controllers, which require climate controlled environment. Sensitivity may be impaired by cushioning effect of heavy snow cover.
Resolution	Required resolution of 0.028 m^3 can be accomplished with appropriate sensor location, radar bandwidth and hardware dimensions (linear track). Note that focus on small object detection will compromise areal coverage.	A cable buried 300 – 900 mm deep can detect dropped weights on the order of 15 to 25 kg at a distance of 3 m; less if the soil is clayey due to signal attenuation. The sensitivity to similarly sized rolling weights is not known.
Creep Detection	Represents the real strength of radar interferometry. Rates as low as 1 mm per month are detectable over a wide areal extent of the surrounding terrain.	No data available. Ground movement in the immediate vicinity of the cable will cause straining, which will be detectable, but needs more research to validate/quantify.

Criterion	GB-InSAR	Secure Pipe™
Output	Fixed station can monitor 2 x 2 km slope region 24/7; mobile platform can extend scan length by many kilometres but with reduced temporal coverage. Deformation maps are generated by the difference in image pairs. Automation of this process should be possible for the fixed station, thereby minimizing turnaround time, but human intervention will be required for image geo-referencing in a mobile system. Re-imaging allows for false trigger detection. Since the system is always live (barring power interruption), no reset is needed.	A single controller can monitor 80 km of track and locate events to ±150 m, possibly better depending on the frequency generated by the impactor. Optimal signal filtering methodologies will need to be established to minimize false triggers. The system is always on and requires no reset. It will automatically re-boot following a power interruption.
Robustness	The system can be designed to an appropriate level of environmental tolerance by using hardened electronics and a reinforced housing.	The system is extremely rugged as the sensor cable is buried (i.e., not exposed) and the controller is housed in an appropriately designed structure and designed with redundancy in key components.
Cost	**ALL COSTS ARE IN CAN$** System development cost is estimated at $1.275 million. Production units are estimated at $0.25 million. Exclusive of development, capital cost of four units to provide intermittent temporal coverage over 10,000 km is $0.10/m. Approximate cost of same to provide continuous coverage in high-risk fixed locations is on the order of $125/m. Operating costs are estimated at $0.0044/m for intermittent coverage to $5.50/m for continuous coverage.	**ALL COSTS ARE IN US$** No estimate of the cost to refine/optimize the system for railway right-of-way monitoring was provided. Capital cost of hardware/installation is $10/m (assuming 80 km lineal coverage; more if reduced extent); trenching and fabrication of controller housing would be extra. Operating costs are estimated at <$0.01/m, exclusive of labour and related expenses borne by the owner.
Vandalism	As with any surface installation, the system and supporting infrastructure are vulnerable to wilful damage. Means of mitigating its susceptibility can be incorporated in the design.	There is little risk of vandalism to the buried sensor cable. The controller housing can be designed to mitigate susceptibility to vandalism.

4 Conclusions

Procedures have been established for preliminary, comparative assessments of technologies to be used in the detection of natural hazards to railway rights-of-way. These include a ranking matrix for a quick determination of relative capability (exclusive of financial implications) and a reporting format whereby a pre-feasibility assessment of attractive alternatives can be effected. Some 26 technologies were subsequently ranked and two leading contenders, GB-InSAR and Secure Pipe™, were selected for further evaluation.

GB-InSAR can detect, either quantitatively by signal phase differencing or qualitatively by decorrelation (resulting from an apparent change in the dielectric properties of the reflector), surface changes to the terrain along the right of way. A single fixed platform

system is, however, limited to a short length of track (on the order of 1 to 2 km depending on resolution requirements). Mobile platforms can provide extended coverage but are not applicable to hazards other than slowly developing slope instability. GB-InSAR is unparalleled in detecting small movements over wide areas, facilitating understanding of causative mechanisms of slope instability and often enabling sufficient advance warning for effective measures to be implemented. Systems such as LISA have been built for this purpose but are not commercially available.

GB-InSAR remains unproven for small object detection such as needed for rockfall monitoring. It also requires significant development to reduce processing times and become near real-time in terms of hazard warning capability. Provider X is eager to pursue the development this technology further and has expressed a desire to jointly pursue avenues of funding for such development.

Secure Pipe™ represents an improvement over the conventional trip-wire detection system. It remains active following an incident (with the exception of major devastation) and has the capability of also detecting other hazards (e.g. localized washout). It can provide continuous coverage over extensive distances (up to 80 km per controller) and the same sensing fibres can be used to transmit data from conventional monitoring instrumentation. However, as with the trip-wire, it is subject to false triggering (which may be reduced by filtering, following field trials and experience accumulation). Its current application is in providing hazard or encroachment warning for buried pipelines.

Turnkey systems are commercially available from Future Fibre Technologies Pty. Ltd. but these will require additional development on the processing side for application to railway hazard detection. FFT has extended an offer to Canadian National Railway and to Canadian Pacific Railway to visit an operational system to see, first hand, how background noise is dealt with and to become better acquainted with the capabilities of the system through live trials.

While both systems offer advantages over existing measures, neither yet represents the optimal alternative. Indeed, it is unlikely that any single technology will satisfy all the requirements of hazard detection. However, both represent viable solutions in specific circumstances and their further development should be supported.

Appendix A
Future Fibre Technologies Submission

1. INTRODUCTION

Future Fibre Technologies Pty. Ltd. (FFT) is an Australian based development and manufacturing company, specializing in distributed, fiber optic based, sensing systems for the security and safety sectors. FFT was established in March 1994 and presently has offices in Australia, Singapore and USA. There are also eleven international, accredited Distribution Partners who cover most of the globe.

FFT has several core, patented technologies that are applied to three main Products, these being:

- Secure Fence™: Developed specifically for large perimeters or country borders, Secure Fence uses standard fiber optic cable as a distributed sensor. The sensing cable is either attached to a fence or buried below the ground to detect ***and locate*** the presence of an intruder to within 25 meters. Secure Fence will detect and locate climbing, cutting, spreading or jacking of the fence or the fence fabric.
- Secure Pipe™: Developed specifically for the Oil and Gas industry, Secure Pipe will detect ***and locate*** surface activity that may become a threat to the pipeline or the adjacent fiber optic communications cable to within 150 meters. Secure Pipe will detect and locate excavation activity (both mechanical and by hand), seismic activity, landslides, subsidence and other similar activities. In the railway application, FFT's Secure Pipe system would be adapted to detect and locate rock falls, landslides and similar activities that would become a threat to the rail traffic. Depending on the depth at which the sensing cable is buried, the system is capable of detecting and locating a rock, weighing as little as 5 kg, falling from a height of 1 meter onto the rail line.
- Secure Link™: There is a misconception that fiber data/comms networks are difficult to "tap". In reality, there are many "off-the-shelf" devices, that are readily available, that allows information to be tapped from a fiber network without the knowledge of the service provider. FFT's Secure Link will detect & locate any tapping device that is fitted to a fiber network to within 25 meters without interfering with the communications signals.

2. TECHNOLOGY

FFT's technology is based on a photonic interferometer. Basically, laser light is pumped through 2 separate fibers in a fiber optic cable. When a disturbance, such as sound waves and vibrations created by excavation at the surface, is applied to the cable, the light is "interfered" with and the sensing controller detects this disturbance. The disturbance in each of the 2 fibers is compared & analyzed to allow us to determine the type of event & to also pinpoint the location. In the case of Secure Pipe™, FFT generally uses the existing fiber communications cable that is laid beside the pipeline. However, it is relatively inexpensive to install new cable if there is no present facility. The cable is normally buried 1.0 – 2.0 meters below the surface and it can be placed inside a conduit if required. Depending on the end user's requirements, the cable can be buried at various depths, from 0.3 meters to greater than 3 meters.

In the rail application, it is envisaged that the sensing cable will be buried between 150 and 300 mm below the surface of the ballast. Trials will be conducted to determine the optimum laying depth and cable construction as well as validating system sensitivity to events and ability to filter train noise.

Each event or threat will have it's own frequency as well as generating different amplitudes, strain, stress, etc on the cable. With this information, we are able to determine the type of event and then discriminate between real threats and false/nuisance alarms. In the case of rock falls, these events generate small to large scale (depending on the size of the rock), high frequency (i.e. sharp) impacts that provide excellent signals for detecting and locating the position of the rock fall. The location of these types of events is generally within 75 meters. In the case of landslides, these events generate large, low frequency signals, which are far different to activities such as rail traffic, excavation and other similar events. The location of these types of events is generally within 150 meters.

This same technology has been applied to the rail transport sector to identify flat spots and cracks in rolling stock wheels.

2.1. Supplier

Company: Future Fibre Technologies Pty. Ltd.
Contact Person: Rob Broomfield
Address: 10 Hartnett Close, Mulgrave, Victoria 3170, Australia.
Telephone: +61 3 9590-3100
Fax: +61 3 9560-8000
Email: rbroomfield@fft.com.au

2.2. Clients

Because of the nature of FFT's business and its client base, we do not provide client reference details until such time as it is appropriate i.e. formal agreement is in place.

FFT has more than 125 installations globally and some of our clients include:

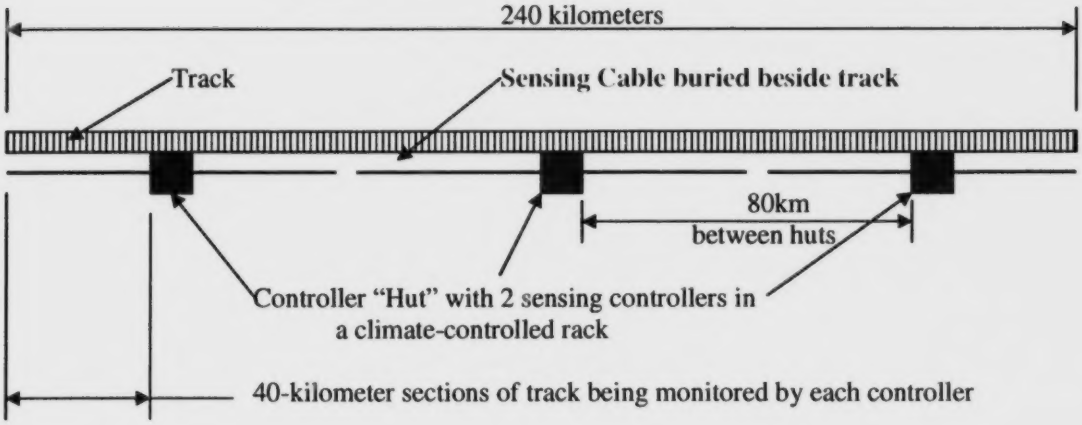
- US Army
- US Department of Homeland Security
- British Petroleum (BP)
- Singapore Ministry of Defence
- Tesoro Petroleum
- US Border Patrol
- Australian Attorney General's Office
- Australian Department of Defence
- Gulf Resources
- Duke Energy
- Credit Suisse First Boston
- NATO

3. SYSTEM DESCRIPTION

The system that FFT proposes for detecting and locating landslides across or near the Canadian rail network comprises:

- FFT Secure Pipe Sensing Controllers: Each controller will monitor 40 km of rail track, depending on cable configuration, with multiple controllers being networked to cover hundreds or thousands of kilometers.
- Sensing cable: This is a single mode, fiber optic cable that will be buried beside the rail line (depth to be determined to optimize performance). This cable can also be used to carry communications along the entire route. Many of our clients lease or sell the spare capacity to other parties such as telecommunications providers.
- Start and End Sensors: Each controller section will require a pair of start and end sensors. The sensing controller is normally located in a secure building (can be several km from the rail track), with a "lead-in" cable connected from the controller to the "start" sensor, which would be located at the beginning of the track section to be monitored. The "start" sensor is in turn connected to the sensing cable. At the 40km point (i.e. 40 km from the start sensor) the "end" sensor is connected to the sensing cable, which completes the 40 km sensing section. This approach is repeated for the length of the track.
- Central Alarm Monitoring System (CAMS): CAMS is used as the "front end" Graphical User Interface (GUI) to connect all FFT Sensing Controllers to a central monitoring point. The Canadian Rail Network, or specific sections thereof, would be displayed on the PC screen. If a landslide occurred that created a threat to the rail track integrity, the specific location of the natural hazard (e.g. rock fall or landslide) would be graphically displayed on the PC monitor along with a dialogue box, which would provide the operator with detailed information on the location, time, date, etc of the rock fall/landslide. CAMS can also notify other parties of the incident by way of email, SMS, etc.
- Climate controlled equipment rack: The sensing controllers must be installed in a climate-controlled rack (20°C ±5°C) to ensure optimal performance and stability. Two controllers are installed in each rack; one to monitor one direction e.g. eastbound while the second controller monitors the section running westbound. The diagram below provides a basic overview of a typical installation.

CAMS Workstation Networked to all Sensing Controllers



Basic overview of multiple system connection.
(Example Only. System can be scaled to cover thousands of kilometers.)

3.1. Operation

The FFT Sensing Controllers are built from Industrial or Military specified components, which are housed in an Industrial Computer. Over 80% of FFT installations are deployed in high security Military/Government applications and have been operational for more than 5 years. The systems are robust and reliable but periodic maintenance of filters, defragmentation of computer hard drives, etc is recommended to ensure trouble free operation.

In addition to the climate controlled rack, it is important to have the sensing controllers protected and backed-up by a filtered UPS. Each controller has a redundant power supply and a mirrored/redundant hard drive to avoid system failure. All events are logged to a database for reference, tracking and faultfinding.

The system is immune to RFI, EMI, lightning strikes, etc. Apart from the control huts, there are no other power requirements in the field as the cable is a passive device. Power requirements for each hut would be approximately 2 kilowatts.

The operation of the system is simple. FFT's philosophy for monitoring the system is to operate on the principle of Automatic Management By Exception Reporting (AMBER). This means that the system only reports events that are threatening and need action or intervention. Using this principle, the operator does not need to be tied to a monitor 24 hours a day, seven days a week

waiting for something to happen. There is the possibility for CAMS to interface with the Railways traffic monitoring system so that it will instantly alert an operator if a landslide occurs.

3.1.1. Fair Weather Conditions

The system is unaffected by extremes of weather, as long as the sensing controllers are in a climate controlled rack.

3.1.2. Poor Weather Conditions

In the rail application, the cable will be buried so it will be unaffected by rain or snow. There may be an instance where minor snow slides will go undetected if there is a heavy cover of snow already on the track and surrounding areas.

3.1.3. Severe Weather Conditions

This is probably the same as 3.1.2 above. Washouts from heavy rain or avalanches should be detected.

3.2. Small Object Detection

The FFT system is capable of detecting and locating many different types of activities but there may be limitations with a single system because of the need to eliminate nuisance alarms from passing trains. In this case, it may be a safer option to use two side by side systems, possibly in the same cable, with one system programmed to monitor for rock falls while the other monitors landslides, earth movement, etc.

This concept could be expanded to use 2 separate cables, one beside the track & the other on the "uphill" side of the track. In this arrangement, the "uphill" sensing cable would be used to detect rolling or bounding rocks as they careered down the hill while the second would detect those rocks that impacted/landed on or beside the track. This arrangement would significantly increase to probability of detecting a rock that gently rolled onto the track if it lost momentum.

3.3. Creep Detection

This is a difficult requirement to quantify, as we have not conducted any empirical measurement along train tracks. We assume there will be some form of creep as a train passes any given point, which we will need to ignore if it does not create a threat to the integrity of the track. Given the fact that the sensing cable is in intimate contact with the surrounding soil, ballast, etc, any soil movement will create a strain on the cable, which will be detected. This could be measured in millimeters but we have no data to verify this.

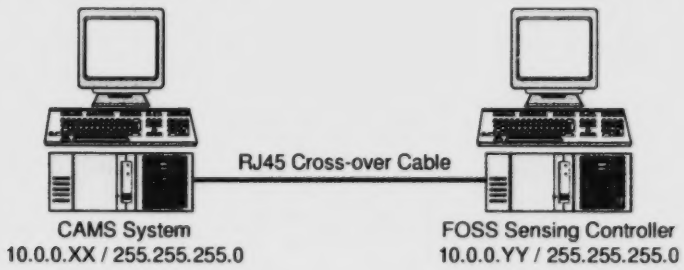
3.4. Data: Capture, Output and Access

CAMS can utilize a satellite image, AutoCAD drawings, bitmaps, etc to form the basis of the rail network layout. By using the CAMS drawing editor, the installer simply draws lines beside the tracks and associates these with each controller section. These sections appear as "green" lines on the map, informing the operator that there are no threats to the rail network. When an incident occurs, the particular section flashes "red", an audible tone is activated, a dialogue box appears with details of the location of the event along with the time and date plus any other client specific requirements i.e. action list, persons to be contacted, etc.

CAMS can interface with many third party devices to activate alarms, lights, cameras, email, SMS, etc.

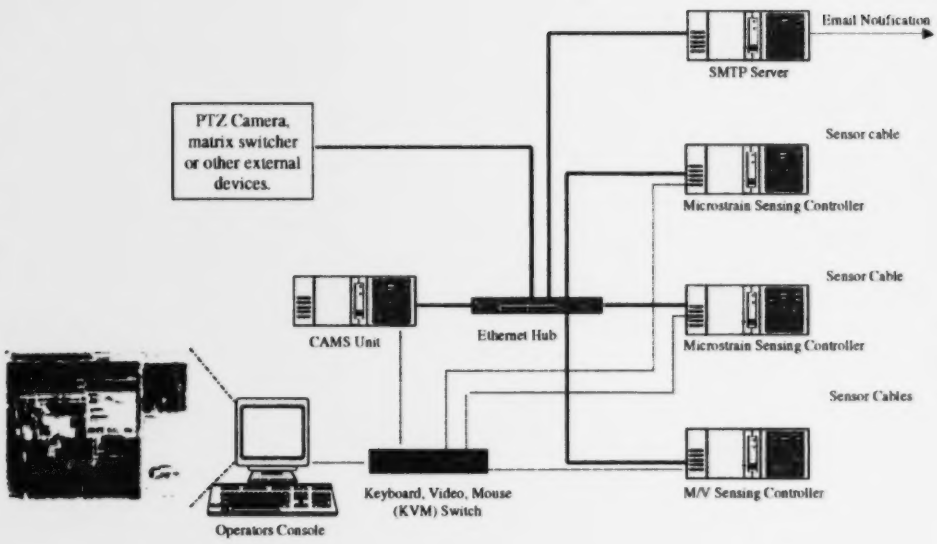
Overview

CAMS is designed to run on separate PC's and Sensing Controllers networked together. One PC running the CAMS software and one or more running the FOSS software. In its simplest implementation, it is as follows:



Simple CAMS System Configuration

You will note that the two systems have different IP addresses, but within the same subnet. Instead of a cross-over cable, or if more than one FOSS unit is to be included, you will need to use a hub to connect all Sensing Controllers and the CAMS unit to your network.



Typical CAMS Installation

Note: You can also have multiple CAMS units monitoring multiple Sensing Controllers.

CAMS System Requirements

Note: CAMS requires a <u>dedicated</u> PC to run on with the following configuration. Attempting to run CAMS on a PC shared with other applications is unsupported and may cause problems both with the installation and operation of the system. FFT will only support CAMS on a dedicated PC that meets the minimum hardware and software requirements outlined below.

Hardware

The CAMS software requires a PC with the following minimum configuration:

- Pentium 4 processor
- 256 MB RAM
- 40 GB HDD (requires 100 MB of free space)
- CD Drive – preferably a CD R/W
- 32MB Video Card (64MB recommended)
- 10/100base-T LAN Interface
- 17" Monitor
- Keyboard & mouse
- Optional Serial/Parallel/USB ports for printer support

Software

CAMS requires one of the following operating systems to run:

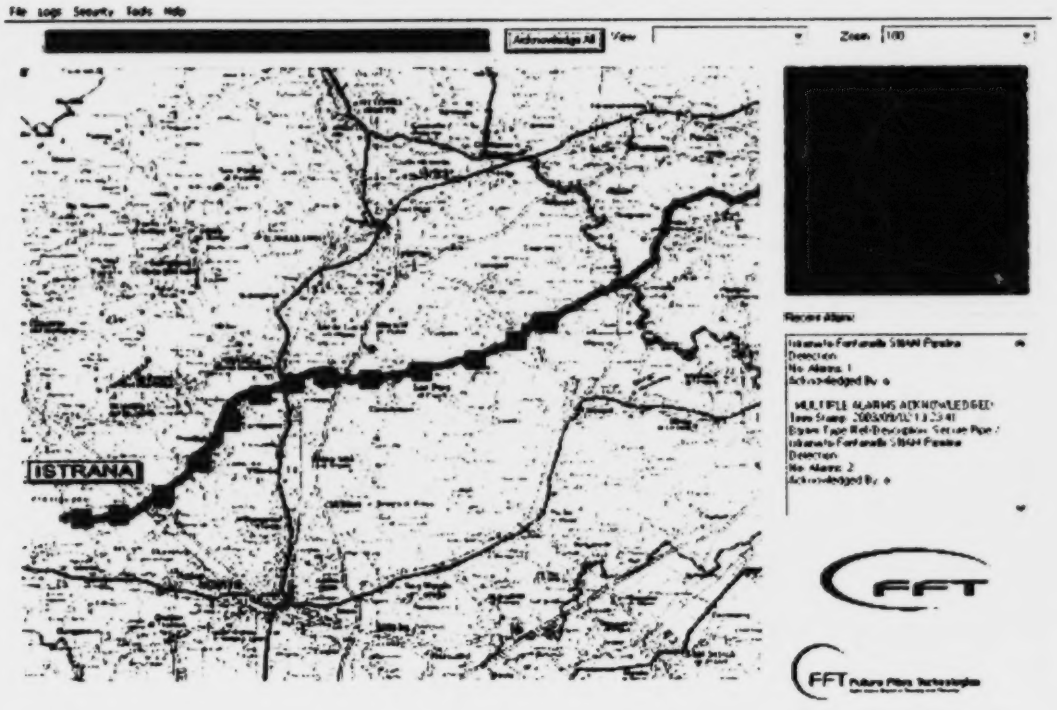
- Microsoft Windows NT4.0 Service Pack 6 or higher
- Windows 2000 Professional Service Pack 4 or higher
- Windows XP Professional

CAMS also requires the following software to function correctly:

- Internet Explorer 6.0 or newer

The CAMS Operator Screen

Double-click on the CAMS desktop icon, and you will be presented with a screen similar to the following after CAMS starts up. Naturally, this screen will be tailored to your particular site.



Secure Pipe Operator Screen After Installation of CAMS

CAMS has multiple login levels, with each level having different capabilities & accesses. These levels can be assigned and tailored to individual users.

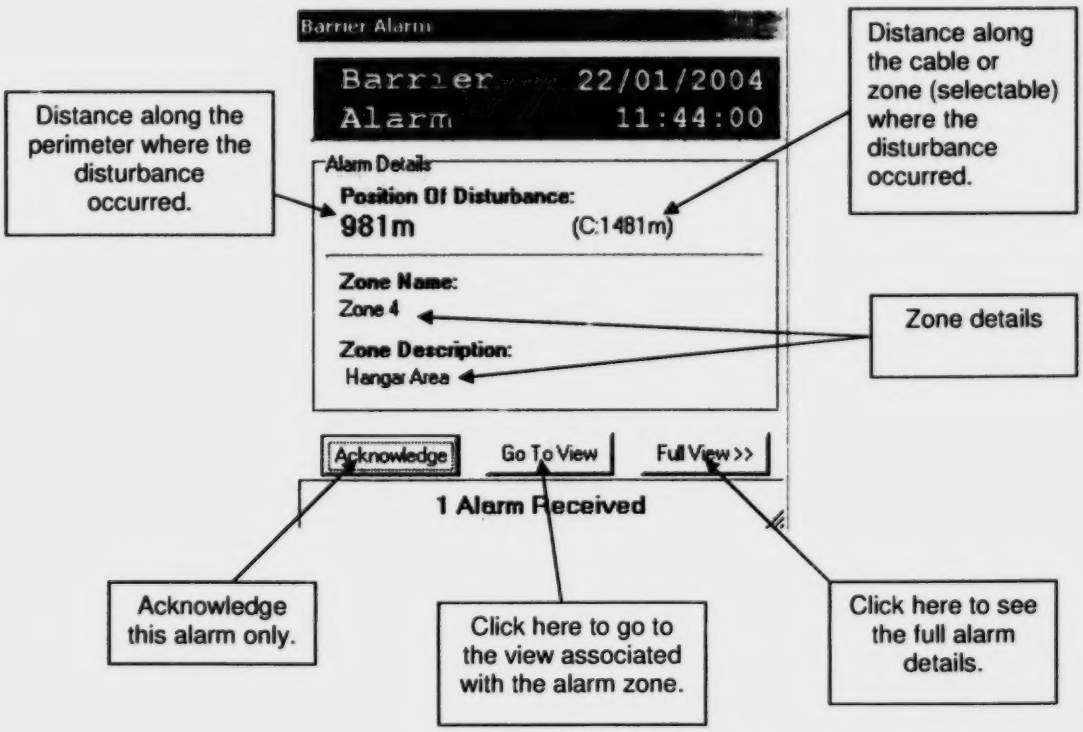
The defaults are:

User	Level
Installer	4
Engineer	3
Supervisor	2
Operator	1

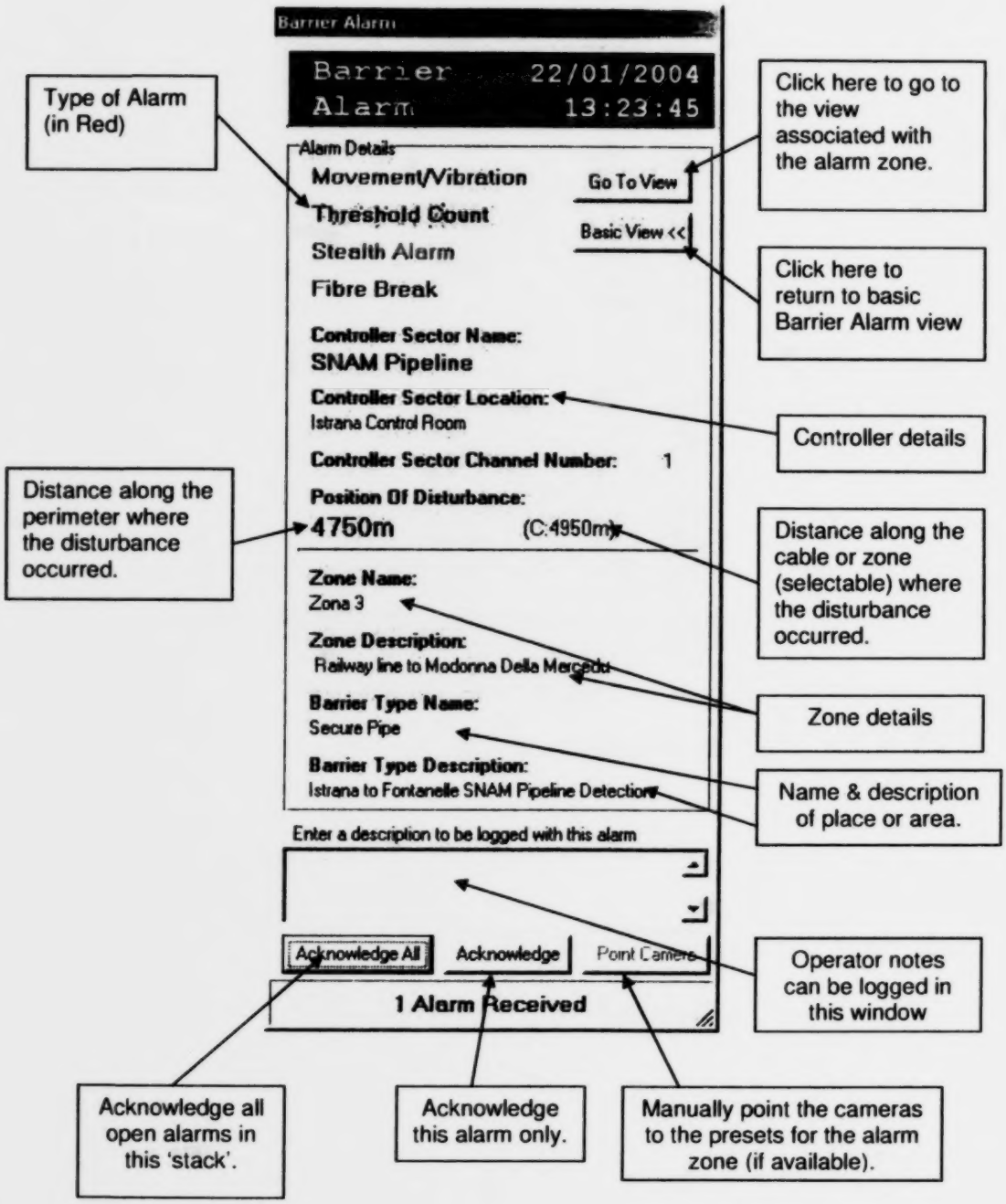
The Alarm Panel

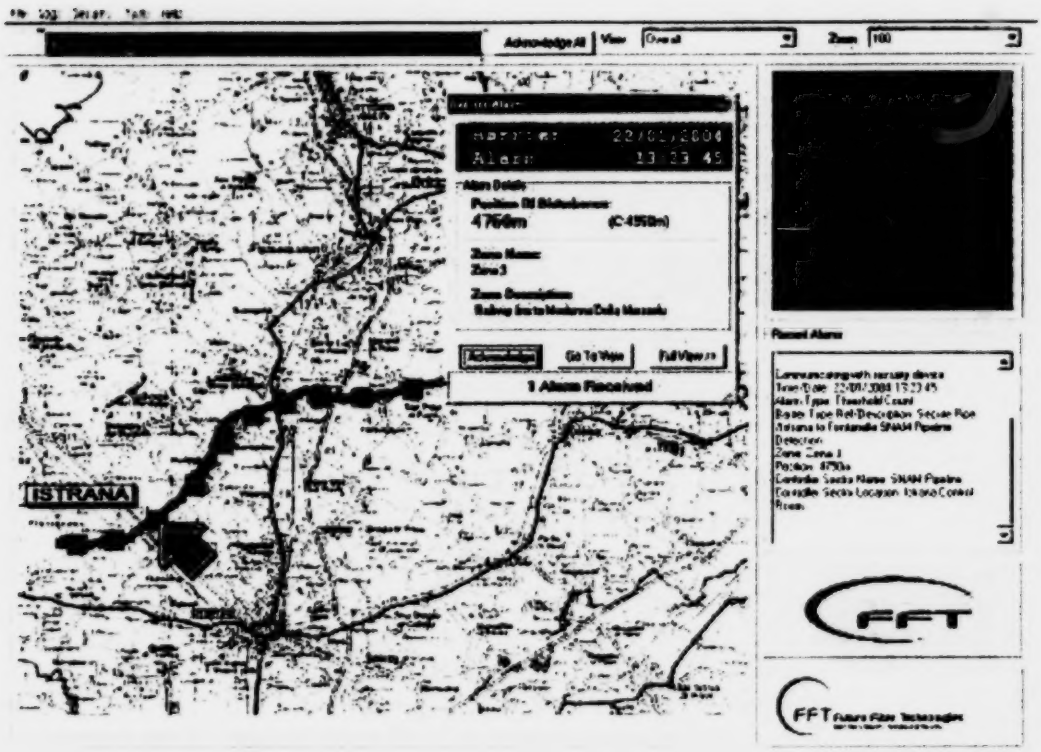
When an alarm occurs, the following screen is presented, along with the basic pop-up Barrier Alarm screen.

When an alarm occurs, the first Barrier Alarm screen that appears is the Basic View as follows:



When you click on ***Full View***, the following screen appears showing the full alarm details:


Barrier Alarm
Barrier 22/01/2004
Alarm 13:23:45
Alarm Details
Movement/Vibration
Threshold Count
Stealth Alarm
Fibre Break
Go To View
Basic View <<
Controller Sector Name:
SNAM Pipeline
Controller Sector Location:
Istrana Control Room
Controller Sector Channel Number: 1
Position Of Disturbance:
4750m (C:4950m)
Zone Name:
Zona 3
Zone Description:
Railway line to Madonna Della Mercede
Barrier Type Name:
Secure Pipe
Barrier Type Description:
Istrana to Fontanelle SNAM Pipeline Detection
Enter a description to be logged with this alarm
Acknowledge All
Acknowledge
Point Camera
1 Alarm Received
Type of Alarm (in Red)
Click here to go to the view associated with the alarm zone.
Click here to return to basic Barrier Alarm view
Controller details
Distance along the perimeter where the disturbance occurred.
Distance along the cable or zone (selectable) where the disturbance occurred.
Zone details
Name & description of place or area.
Operator notes can be logged in this window
Acknowledge all open alarms in this 'stack'.
Acknowledge this alarm only.
Manually point the cameras to the presets for the alarm zone (if available).



Typical CAMS Alarm Screen

3.4.1. False Trigger Susceptibility

The primary challenge will be to develop filtering techniques to "ignore" trains, particularly when they have been stationary and begin to move, as they will generate concentrated, low frequency vibrations. This may mean that the triggering of a threat event is delayed for a short period while the system determines if the "event" is moving along the tracks (i.e. a train) or is isolated to one area (i.e. landslide).

3.4.2. Automatic or Remote Reset Capabilities

The FFT Secure Pipe sensing controller will automatically re-boot after a power failure. However, FFT strongly recommends the use of a suitable, filtered UPS to ensure uninterrupted system performance.

4. SYSTEM LIMITATIONS

The following are limitations of the system:

- The sensing controllers must be housed in a climate-controlled rack with a suitable UPS.
- The hard drives should be defragmented every 6 months to ensure optimum performance.
- Fan filters should be replaced at least once per year.
- A single controller has the capability of monitoring 40 km of rail line, depending on cable configuration, however this is conditional upon the use of quality optical cable and splices. Poor quality of cable and splices will reduce the effective length.
- If the cable is cut or broken, the sensing controller attached to that particular section of cable would go into alarm; report the location of the cut and will become inoperative until the cable is repaired.
- The system will not detect snowdrifts and may have difficulty detecting small snow slides if the track and surrounding area is covered in deep snow.

5. SYSTEM MAINTENANCE & COST

5.1. Maintenance Zone

Information was not available.

5.1.1. Component Ruggedness

The system is extremely rugged with no known areas of weakness. Each controller is fitted with a redundant power supply and redundant/mirrored hard drives. All other components are solid state. The laser has a 15-year life expectancy and the cable has a life expectancy (underground) of 25+ years.

5.2. Cost (indicative only)

Based on 80-kilometer sections (i.e. 2 sensing controllers back-to-back in a common climate controlled rack), the cost for each 80-kilometer section, excluding cable installation, the erection of any control huts, provision of power to huts and other similar infrastructure, is as follows. Two scenarios have been provided; the first using FFT sensing cable and the second using existing fiber infrastructure, assuming the latter is suitable (e.g. type, quality, location/proximity to track, depth, etc).

1. FFT supplied cable: US$1,208,000 per 80-kilometer section of track.
2. Existing cable: US$648,000 per 80-kilometer section of track.

In addition to either scenario, CAMS will be required to network all sensing controllers and to provide the operator interface. CAMS will cost US$15,000 for the entire rail network plus any expenses incurred in setting up specific site maps or special requirements.

5.2.1. Capital

Table 1 : Required Capital Cost (Scenario 1: FFT supplied cable)

Material	Cost US$
Hardware	$457,000.00
Cable	$640,000.00
Services, including FFT equipment installation and supervision of cable laying.	$85,000.00
Travel, living, etc	$26,000.00
Installation of cable	Not included
Total Cost	**$1,208,000.00**
Track Length	**80,000 m**
Cost per meter	**US$15.10**

Required Capital Cost (Scenario 2: Client supplied cable)

Material	Cost US$
Hardware	$457,000.00
License fee	$80,000.00
Services, including FFT equipment installation	$85,000.00
Travel, living, etc	$26,000.00
Installation of cable	Not included
Total Cost	**$648,000.00**
Track Length	**80,000 m**
Cost per meter	**US$8.10**

In either case, CAMS will also be required for the total system, regardless of the length of the track. This will cost an additional US$15,000 plus any expenses incurred in setting up specific site maps or special requirements.

5.2.2. Operating / Maintenance

Table 3 summarizes the required monthly maintenance costs.

Table : EXAMPLE Required Monthly Cost per 80 km section

Material	Quantity	Unit	Unit Cost	Cost
Energy	3	kW/hr.	$1.00[1]	$3.00
Fan filter (once every 12 months)	2	Nr.	$30.00	$60.00
			TOTAL	**$388.00**
Track Length	80,000	m		
		Cost per meter		**$0.00485**

5.3. Vandalism

The sensing controllers should be housed in a secure, vandal proof building. The sensing cable is buried and is of little commercial value so there is little risk of vandalism or theft.

Appendix B
Ground-based SAR Interferometry for Monitoring Mass Movements

Original Paper

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Ground-based SAR interferometry for monitoring mass movements

Abstract An innovative technique for the remote assessment of ground displacements, based on radar interferometry and implemented using ground-based instrumentation (GB-InSAR), has been tested in recent years on a number of selected case sites. The system, known as LISA, developed by the Joint Research Centre (JRC) of the European Commission, is a ground-based radar interferometer specifically designed for field use. It is composed of two radar antennas mounted on a linear rail which horizontally slides to form a synthetic aperture. Coherent SAR processing converts the raw data into an image containing, for each pixel, information on the wave phase, which depends on the target-sensor distance. Consecutive couples of SAR images can be cross-correlated to form interferograms representing phase variations which can be directly related to ground displacement along the sight-line of the radar system, since they are acquired from exactly the same position. Several applications of the system have been conducted on a number of mass movements located in Italy, in order to validate the technique for the monitoring of landslides. GB-InSAR has proved its potential for the measurement of the superficial ground displacements of different landslide types, in terms of failure mechanism, materials involved, kinematics, water content and deformation rates. In particular conditions, such as fast-moving phenomena and inaccessible areas, the technique can be employed directly as a monitoring tool, providing multi-temporal displacement maps of the observed area. Additionally, some applications of the GB-InSAR have provided a fundamental support to decision makers during landslide emergencies, allowing the civil protection authorities to assess the risk and to manage an effective emergency response.

Keywords Landslide · Monitoring · Ground-based SAR · Interferometry · Remote sensing · Emergency management

Introduction

The first application of space-borne SAR interferometry (InSAR) to the study of natural phenomena was in the 1970s. Since then it has been successfully applied to the observation of different geophysical problems which induce terrain deformations, such as volcanic activity, earthquakes and land subsidence (Massonnet and Feigl 1998). This trend has grown, especially during the last 10 years, due to the availability of a large amount of SAR data acquired from different satellites. The interest in applying InSAR for environmental studies is related to its capability of obtaining two-dimensional deformation maps of the area under observation by using a remote sensing technique. Unfortunately, the characteristics of slope instability phenomena are not compatible with the acquisition parameters of the current space-borne SAR missions, such as spatial resolution, revisiting time and view geometry. Therefore, results have not been as good as those for other geophysical applications, with the exception of some individual cases (Fruneau et al. 1996; Kimura and Yamaguchi 2000). However, the use of ground-based SAR interferometry (GB-InSAR) is as effective as space-borne SAR interferometry, in the sense of spatially-distributed information and the independence from weather and light conditions. In addition, it eliminates some of the drawbacks related to satellite platforms and provides a greater flexibility in terms of its operation and the acquisition parameters (Tarchi et al. 2003a, 2003b). This paper will explain the main characteristics of ground-based SAR interferometry, demonstrating how it can be employed as a tool for landslide monitoring and emergency management.

The first applications of the GB-InSAR were devoted to the evaluation of the accuracy of the new technique, by comparing the SAR data with those acquired by conventional topographic and geotechnical instrumentation (Fig. 1). In particular, the validation phase has allowed us to demonstrate the high accuracy of the GB-InSAR on the assessment of displacement fields and its advantages with respect to traditional methods (GPS, EDM and extensometers). Further, radar campaigns, varying from a span of few days to several months, have shown the potential of the technique in different operational conditions. In fact, the 2D deformation maps provided by GB-InSAR can be used for a complete assessment of the landslide dynamics during a phase of emergency.

Methods and equipment

The Linear SAR (LISA) system, shown in Fig. 2, is a ground-based Synthetic Aperture Radar (GB-SAR) developed by the Joint Research Centre (JRC) of the European Commission. The system, specifically designed for outdoor applications, has been extensively tested in different fields, such as landmine detection, biomass estimations and interferometric monitoring of large man-made structures (Rudolf et al. 1999; Tarchi et al. 1997, 1999, 2000). The hardware consists of a continuous-wave step-frequency (CF-SF) radar based on a network analyser for generating the microwave signal. The synthetic aperture is obtained by sliding a motorised sled housing the transmitting (TX) and receiving (RX) antennas, as well as other microwave components, along a linear rail. The whole system is controlled by a portable computer (PC) where the acquired data are stored for further processing. Four versions of the LISA system have been produced by the JRC differing only in terms of the rail length (from 1 to 5 m). The radar system operates in the Ku, C and L frequency bands, with a complete coverage of the band between 0.3 and 6 GHz. It has full polarimetric capabilities and the band interval between 14.5 and 18 GHz had VV polarization.

Along the synthetic aperture the antennas are moved at regular intervals every few millimetres, and for each position along the rail the frequency band is scanned with steps of normally 50/100 kHz. The raw data acquired by the instrument along an entire

Fig. 1 Geographical location of the case studies chosen for the radar monitoring campaigns

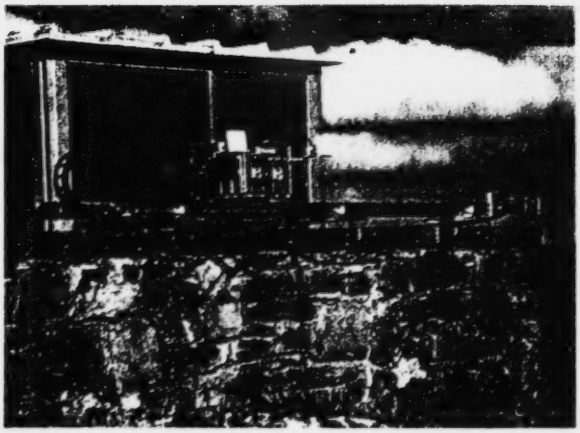

Fig. 2 Field set-up of the ground-based SAR interferometer showing the two antennas and the rail upon which they slide. The prefabricated building behind contains all the electrical components for the system

scan of the rail represents a complex data array in which each element corresponds to a particular position along the rail and a specific frequency band. These data are converted, by using an appropriate time-domain SAR focalisation algorithm (Fortuny and Sieber 1994) into an image which, for each pixel, contains both information on the amplitude and on the phase of the signal. While the former is related to the amount of energy contained in the backscattered signal, the latter is connected to the target-sensor distance. A SAR image is characterized by two spatial resolutions: the range resolution, along the direction perpendicular to the rail, and the azimuth resolution, parallel to the synthetic aperture.

The azimuth resolution Δx varies with the range distance R as:

$$\Delta x = \frac{\lambda R}{2L}$$

where L is the synthetic aperture, and λ the radar wavelength. If the apparatus functions in the Ku ($\lambda \gg 1.7$ cm) or C bands ($\lambda \gg 5.6$ cm) an azimuth resolution of a few meters is obtained. The range resolution is given by:

$$\Delta R = \frac{c}{2B}$$

where c is the light speed and B the bandwidth, which is equal to the radar frequency of B=80 MHz, where ΔR is less than 1 m.

By correctly preserving the phase content of the SAR images it is possible to implement the interferometric processing. The technique is based on the cross-correlation, pixel by pixel, between the phase content of two SAR images of the same area, taken at different times. In fact interferograms, which represent the spatial distribution of the phase difference between the two images, are simply generated by the product of the complex datum of the master image and the conjugate complex datum of the slave image. Acquiring data exactly from the same position (zero-baseline condition) and assuming that the dielectric properties of the observed area are constant in time, the interferometric phase φ is directly related to the ground deformation Δr along the radar line-of-sight (LOS) via the relationship

$$\Delta r = \frac{\lambda}{4\pi}\phi$$

where λ is the radar wavelength. Such that, the value of each pixel, converted from phase values to distances using the central frequency of observation, allows the assessment of the ground displacement in the LOS direction. Negative values indicate a distance reduction, which corresponds to a displacement towards the sensor. To obtain deformation maps from the interferograms, the displacements measured from each couple of consecutive images can be accumulated. This approach normally eliminates all the drawbacks related to the phase unwrapping, induced by the presence of interferometric fringes, such as those displayed in Fig. 3. In fact, deformation values are affected by the intrinsic ambiguity of the phase: if ground displacement towards the sensor exceeds the end of the scale (i.e. 0.25λ=4.5 mm) the successive values will restart from the opposite scale. After a ground displacement of 0.5λ, the image pixels are in phase (value=0). Movements, which exceed 0.5λ generate the interferometric fringes.

The radar system is operational from the target area within a distance interval ranging from a few meters up to several kilometres. The maximum distance in order to obtain good quality radar measurements is largely dependent upon the power of the transmitted signal, which cannot exceed certain values for

Fig. 1 Geographical location of the case studies chosen for the radar monitoring campaigns

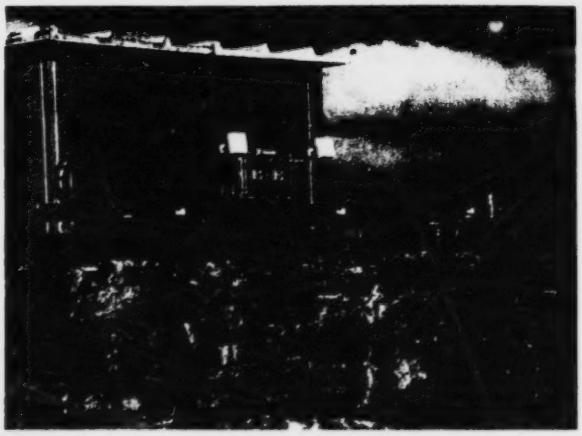

Fig. 2 Field set-up of the ground-based SAR interferometer showing the two antennas and the rail upon which they slide. The prefabricated building behind contains all the electrical components for the system

scan of the rail represents a complex data array in which each element corresponds to a particular position along the rail and a specific frequency band. These data are converted, by using an appropriate time-domain SAR focalisation algorithm (Fortuny and Sieber 1994) into an image which, for each pixel, contains both information on the amplitude and on the phase of the signal. While the former is related to the amount of energy contained in the backscattered signal, the latter is connected to the target-sensor distance. A SAR image is characterized by two spatial resolutions: the range resolution, along the direction perpendicular to the rail, and the azimuth resolution, parallel to the synthetic aperture.

The azimuth resolution Δx varies with the range distance R as:

$$\Delta x = \frac{\lambda R}{2L}$$

where L is the synthetic aperture, and λ the radar wavelength. If the apparatus functions in the Ku ($\lambda \gg 1.7$ cm) or C bands ($\lambda \gg 5.6$ cm) an azimuth resolution of a few meters is obtained. The range resolution is given by:

$$\Delta R = \frac{c}{2B}$$

where c is the light speed and B the bandwidth, which is equal to the radar frequency of B=80 MHz, where ΔR is less than 1 m.

By correctly preserving the phase content of the SAR images it is possible to implement the interferometric processing. The technique is based on the cross-correlation, pixel by pixel, between the phase content of two SAR images of the same area, taken at different times. In fact interferograms, which represent the spatial distribution of the phase difference between the two images, are simply generated by the product of the complex datum of the master image and the conjugate complex datum of the slave image. Acquiring data exactly from the same position (zero-baseline condition) and assuming that the dielectric properties of the observed area are constant in time, the interferometric phase φ is directly related to the ground deformation Δr along the radar line-of-sight (LOS) via the relationship

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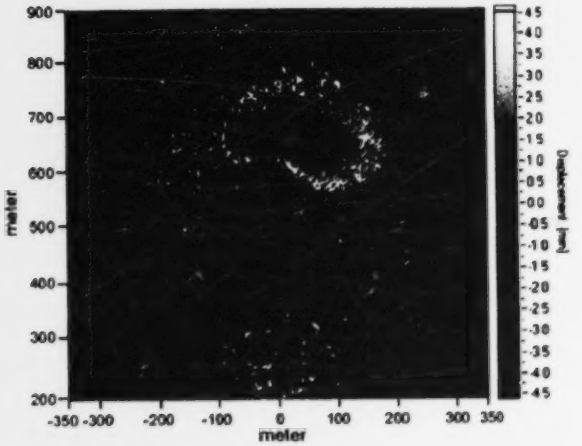

Fig. 3 Interferogram, spanning a temporal interval of 24 h, obtained by the LISA device in the 3-m rail configuration of the Cortenova rock slide (northern Italy). Colours show the range of displacements which occurred in the time span. Each colour corresponds to a LOS displacement of a half signal wavelength

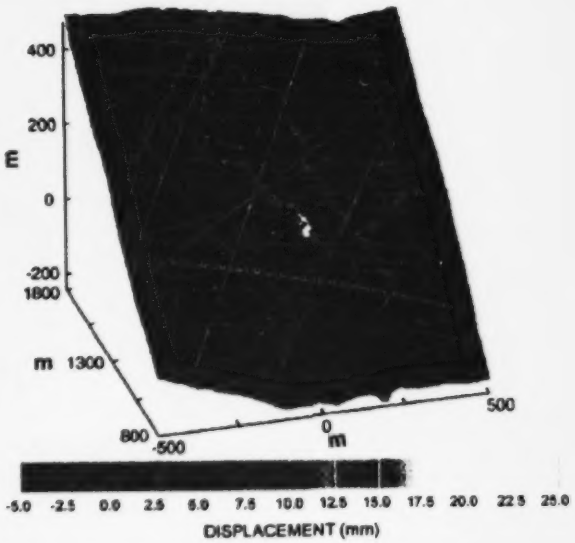

Fig. 4 Cumulated displacement map of the Ruinon rock slide, spanning a time interval of 55 h, shown on a digital elevation model

safety reasons. It is worth noting that the antennas used have a 3-dB beam width of approximately 20°. Thus, the resulting azimuth extent of the antenna footprint varies with respect to the distance from the target and consequently also the dimension of the observed area depends this distance. The time length of a single SAR acquisition is mainly related to the ground-deformation rate of the observed phenomenon and to the minimum technical time required for generating a good quality image. In fact, in order to avoid all the problems connected to the phase ambiguity and phase unwrapping, data should be acquired at time intervals small enough to obtain, between two sequential SAR images, a maximum ground deformation which is shorter than the entire phase cycle. However, the current minimum acquisition length of the ground-based systems developed by the JRC, related to technical reasons, is only a few minutes. This limits the range of velocity detectable with the GB-InSAR of up to a few decimetres per hour.

Outcome from the field tests

In the last three years a number of landslides characterized by different kinematics and material involved have been selected in order to evaluate the capabilities of the technique in the field (Table 1, Fig. 1). The first campaign was carried out in July–August 2000, on the Ruinon rockslide, involving more than 30 million m^3 of material, which is located in Valfurva (Middle Valtellina), in the Raethian Alps (Agliardi et al. 2001). The landslide threatens important transportation routes and if it collapsed it would cause the blockage of the river running along the slopes toe. Since 1987, the slope has been equipped with a monitoring network of extensometers, topographic benchmarks, GPS receivers and inclinometers. The results from a 7-day LISA campaign (Tarchi et al. 2003a), have shown the capability of the technique to supply multi-temporal deformation maps of a rockslide, with displacement rates up to 1.6 mm/h (Fig. 4). Moreover, the analysis has provided radar measurement precision, computed as the standard deviation of the phase difference distribution in the stable areas which is equal to 0.75 mm. The average distance of LISA from the target was about 1,300 m, and the system operated in the frequency band 16.80–16.88 GHz resulting in a spatial resolution of about 2×4 m. The radar data have been compared with those acquired during the same time interval by several automatic extensometers placed within the landslide body and show only a few millimetres of discrepancy.

The Tessina landslide, located in the NE Italian Alps near the city of Belluno (Pasuto et al. 1992; Mantovani et al. 2000), is representative of a complex slope movement with a rotational-translational slide at the source which turns into a channellised mudflow. On this landslide two radar measurement campaigns

Table 1 Summary of the results of the GB-InSAR experiments carried out on several mass movements within Italy

Test site	Date	Landslide type	Max speed (mm/h)	LISA rail length (m)	Validation
Ruinon	July–Aug. 2000	Rock slide	1.6	2	Extensometers
Tessina I	Sept.–Oct. 2000	Earth slide	36	2	Topographic benchmarks
Tessina II	June–July 2001	Earth slide	5.7	2	Topographic benchmarks
Ceriana	Feb.–Mar. 2001	Debris flow/earth flow	-	3	Topographic benchmarks
Firenzuola	May 2002	Rock topple	0.5	2	Distometers
Rocca Pitigliana	Nov. 2002	Earth flow	-	2	GPS
Cortenova	Dec. 2002–Jan. 2003	Rock slide	0.2	2	Distometers
Stromboli	Feb.–Aug. 2003	Rock slide	15	4	-

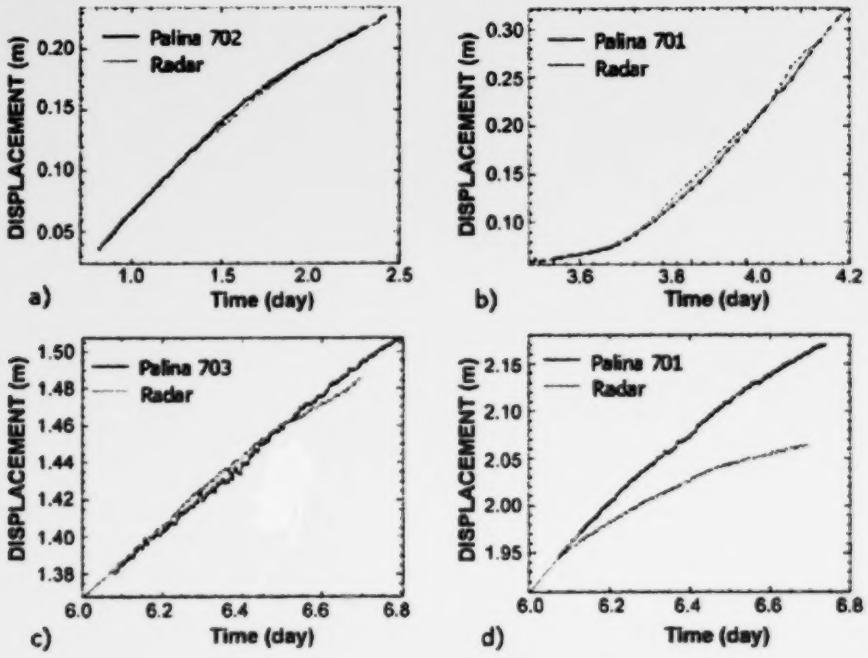

Fig. 5 Comparison between GB-InSAR (*triangle*) and topographic (*rhombus*) displacement measurements performed on the Tessina landslide

have been carried out during 2000–2001, spanning a total time interval of approximately 30 days. The average distance from the target was about 500 m, while the system operated in the frequency band 16.70–16.78 GHz, which resulted in a spatial resolution of about 2×2 m. During the first campaign it was understood that good results could be obtained from the GBInSAR on terrains containing a high water content, variable roughness and high deformation rates (up to several decimetres per day). The second campaign, on the other hand, allowed for the complete validation of the radar measurements with data acquired from an automatic station (Fig. 5). The results are very impressive as the differences between the two datasets are within the expected accuracy of the instrument i.e. a fraction of the radar wavelength (Fig. 5a, b) (Tarchi et al. 2003b; Casagli et al. 2002, 2003). However, a few major discrepancies have been observed, related to different sources. The first one is connected to the differences in the typology of the measurements: the topographic system estimates the position of a point at a particular instant, whilst the GB-InSAR retrieves an average displacement in both time and space (Fig. 5c). The second source of error is related to the drawbacks of the EDM, such as the benchmark tilting with ground movements (Fig. 5d).

The above campaigns have been performed by using the 3 m rail LISA, but in March 2001 the 1-m rail LISA was employed for the first time in an outdoor experiment for the monitoring of the Ceriana debris-flow, NW Italy (Fig. 6). The choice of the different system was related to the distance of the installation site from the target area (about 150 m), short enough to obtain a good spatial resolution using a smaller synthetic aperture. In fact, by using such an aperture and a signal frequency band between 17.00 and 17.20 GHz the average spatial resolution from the obtained SAR images was 0.75×0.75 m and the expected precision lower than 0.3 mm. The experiment was aimed at understanding the evolution of the unstable area which was affected in November 2000 by a large debris-flow triggered by intense rainfalls (Canuti et al. 2003).

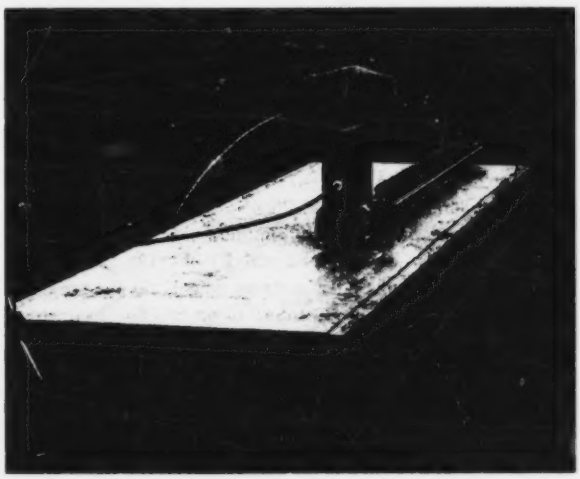

Fig. 6 Picture of the field set-up of the 1-m rail GB-SAR interferometer on the Ceriana test-site

The first operational application of the GBInSAR for landslide monitoring was performed in May 2002 on the Monte Beni rock slide. The main goal of this test was to retrieve deformation field data of a large deep-seated rock slide (volume 1×10^6 m^3), including a local rock toppling phenomena which occurred within the landslide body (Fig. 7). The LISA 3-m rail configuration was placed at an average distance from the target of about 1,800 m. Observations were carried out within the frequency band

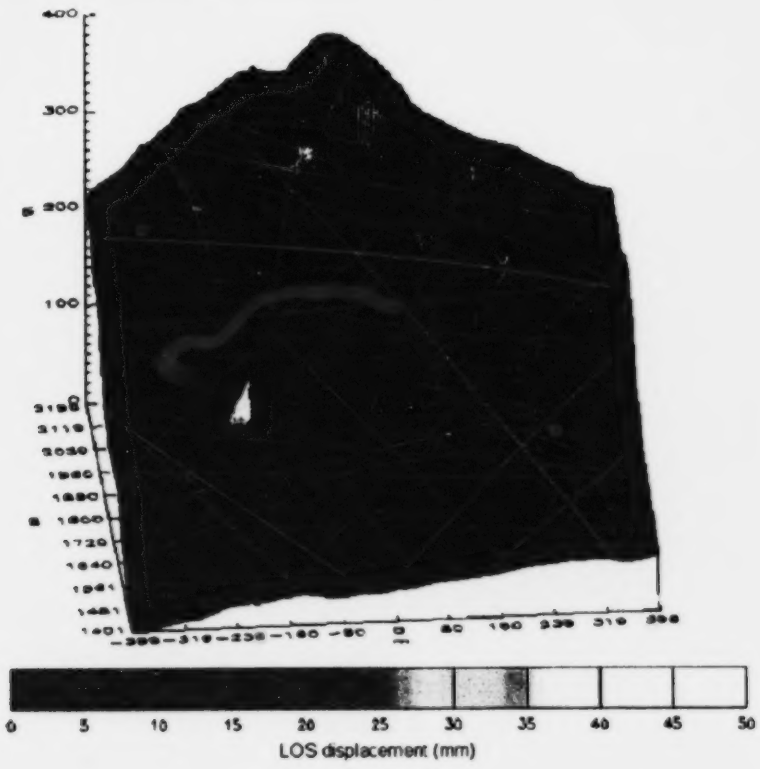

Fig. 7 Cumulated displacement map of the Monte Beni rock slide, shown on a digital elevation model, spanning a temporal period of 124 h. *Colours* show the range of displacements which occurred in the time span

of 16.70–16.76 GHz, obtaining a spatial resolution of approximately 2.5×5 m. From the collected data an assessment was made concerning the limits of the moving zone, which had been impossible to determine using other monitoring systems due to the difficulties in accessing the area. Consequently, the magnitude of the rock slide was also calculated which was necessary for the definition of possible risk scenarios (Casagli et al. 2004).

Before the series of field tests described in this paper it was only possible to evaluate the potential of ground-based SAR interferometry for landslide monitoring from a technical point of view. However, the usefulness of this system has now been demonstrated in varying operational conditions for mass movements characterized by a long term evolution. This was primarily due to the type of campaigns performed which normally spanned a several days. For example, an experiment was carried out in 2002 on the complex landslide at the Roccapitigliana site in the Northern Apennines, Central Italy. This landslide consists of an earth-slide forming the upper part which evolves into an earth-flow at the toe. The average distance from the target was about 400 m, the system operated in the frequency band of 16.70–16.78 GHz, which resulted in a spatial resolution of about 2×2 m. Although the quality of the acquired data, in terms of backscattered signal and phase decorrelation, have confirmed the technical feasibility of the GBInSAR application on this type of mass movement, it was not possible to assess significant ground deformations, as they typically occur as pulse events, triggered by periods of intense rainfalls, (Barbieri et al. 2003). In this case the time span was a crucial factor in assessing the capabilities of the technique. Hence, the last two campaigns performed to date, at Cortenova and Stromboli, have attempted to solve this problem.

At the beginning of December 2002 the village of Cortenova, close to the Lecco Lake, in the Italian Alps, suffered a rock slide comprised of approximately 1×10^6 m^3 of material. After the initial event, which caused the destruction of several buildings and factories, about 900 people living within the expected run-out area were evacuated and the regional civil protection authorities decided to install a ground-based SAR interferometer in order to track the landslide evolution. This action was taken due to the drawbacks in installing other traditional monitoring systems, such as the weather conditions and the difficulties in accessing the landslide mass. From mid December 2002 to April 2003 the radar system collected data continuously, under all weather conditions and working automatically. It was installed at an average distance of about 600 m, operating at the frequency band of 16.70–16.78 GHz. The spatial resolution obtained was about 2×3 m. By using a telephone line the data was transferred daily to the JRC, where they were analysed by skilled operators. The data provided multi-temporal deformation maps of a significant portion of the slope (about 60,000 m^2) affected by residual movements (Fig. 8). The long-term monitoring between December 2002 and April 2003 revealed the gradual decrease of the slope deformation from 5 cm/day to 0.3 cm/day and, as a consequence, the response of the civil protection planning to the reduction in risk (Casagli et al. 2003b).

The final application of GBInSAR for landslide monitoring, which is still in progress today, is related to the slope movements on the Stromboli volcanic island. On 30th December 2002,

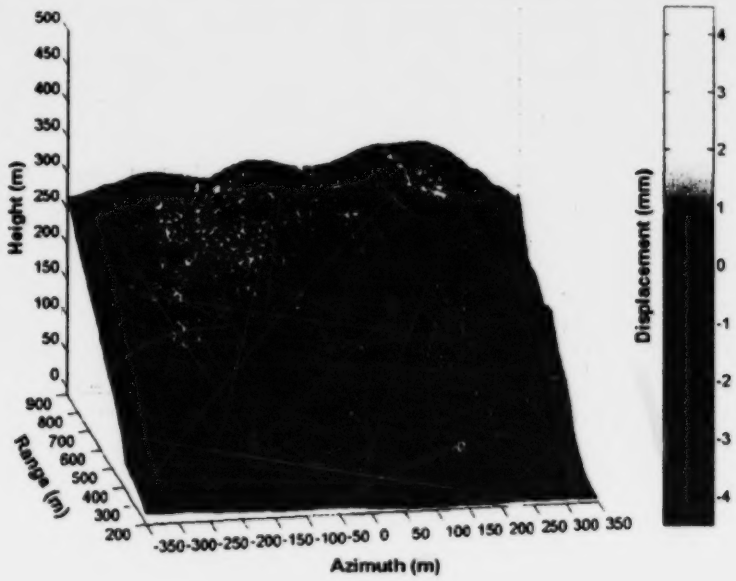

Fig. 8 Displacement maps of the Cortenova rock slide measured on 15 December 2002, spanning a temporal interval of 5 h. The map has been shown on a digital elevation model of the observed area. *Colours* show the range of displacements which occurred in the time span

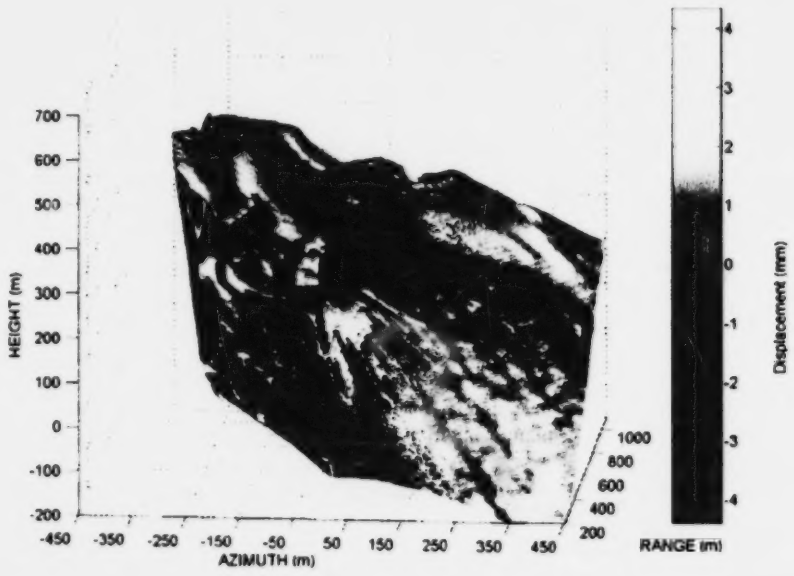

Fig. 9 Displacement map of the Sciara del Fuoco, in Stromboli, spanning a time interval of 1 h, projected on a digital elevation model. *Colours* show the range of displacements which occurred in the time span

following an intensification of the explosive activity of the volcano, a series of landslides involving a total estimated volume of about 30 million m^3 of debris and loose rock, occurred on the steep NW flank (Sciara del Fuoco) towards the sea causing a tsunami. Since February 20th 2003, responding to the National Civil Protection Department request, a specific SAR interferometer made especially for this site, is continuously active, collecting about 120 images a day with a pixel resolution of approximately 2×2 m. The system acquires data from an average distance from the observed area of about 550 m, sweeping the bandwidth of 17.0 to 17.1 GHz. The analysis of the whole dataset acquired up until now has allowed the tracking of the deceleration phase after the 30th December landslide event. Over a time span of 7 months, it has also been possible to distinguish the interaction of different geomorphic processes, such as the lava flows, the gravitational sliding of the volcanoclastic materials on the Sciara along a deep-seated slip surface, and the slow viscous gravitational flow of cooling lava masses accumulated during the recent eruption (Fig. 9).

In order to follow the different velocities of movement, four significant points within the Sciara del Fuoco were selected. Their velocities, extracted from 1-hr interferograms have been plotted against time (Fig. 10). This type of analysis shows the trends in the displacement rates, identifies short-term fluctuations within

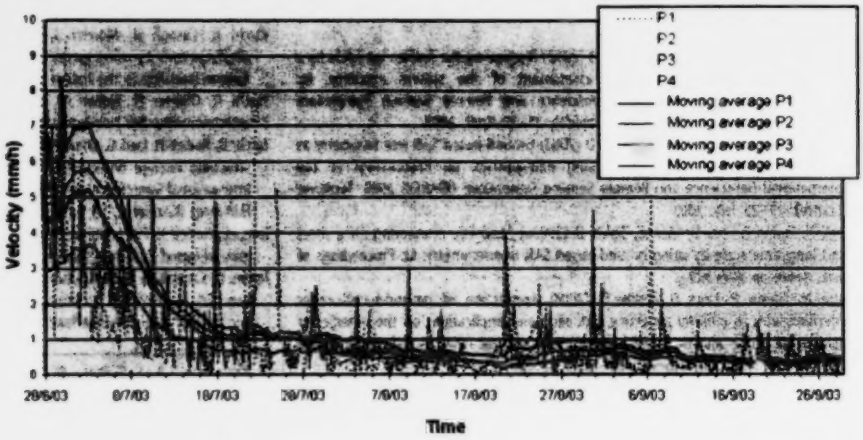

Fig. 10 Velocity in four selected points of the observed area plotted against time every 6 h with a 40-point moving average, from the end of June to September

the velocities, interprets the effects of rapid shallow movements and observes a long-term decrease in the deformation rate. These observations appear in a preliminary report published by Casagli et al. 2004.

These last two campaigns, besides demonstrating that the GBInSAR is capable of operating over long periods in outdoor environments, have also shown the possibility of the technique in becoming an operational tool for landslide monitoring during emergency cases. This in turn, would be a great support to decision makers involved in landslide risk management.

Conclusions

This paper shows the results of applying the GB-InSAR to landslide monitoring, through the application of such a technique to different test-sites (Table 1). The field tests have shown that the technique can provide multi-temporal deformation maps, with a spatial resolution of a few metres and an accuracy in the displacement assessment within millimetres along the system LOS.

It has also been proven that the GB-InSAR is productive on unstable areas with a spatial resolution of up to several square kilometres and characterized by different failure mechanisms, materials involved, kinematics, water content and deformation rates. The results of the GB-InSAR have been compared with other geotechnical instrumentations, showing how its characteristics, such as the spatially distributed information and the remote sensing data can be used to improve the understanding of the deformation field of the observed phenomenon, as well as augmenting the acquisition of data in areas not normally accessible. With respect to the SAR interferometry implemented by satellite the results obtained by using the ground-based system have demonstrated that the technique can overcome all the drawbacks related to the satellite parameters, such as geometrical and temporal decorrelations, phase unwrapping and inability to measure high deformation rates. However, it still maintains the same useful characteristics of the satellite configuration, such as the remote action, the spatially-distributed information and the independence from the weather and light conditions.

By taking into account all the GB-InSAR aspects and the operational capabilities demonstrated during the last field tests, some guidelines related to the use of the system within landslide risk management can be defined. Due to the possibility of obtaining information about the entire observed area, the system can be employed as a support to traditional monitoring networks, in order to obtain information from inaccessible or fast-moving areas and in the design phase, for the optimisation of the sensors arrangement. This allows the installation of instruments in significant positions. The field campaigns have also demonstrated the capability of the system of being employed over long time periods, as a permanent monitoring system, especially for high risk phenomena. Indeed, the short time needed for installing the instrumentation and the flexibility in terms of the acquisition parameters make GB-InSAR a robust system for landslide monitoring during emergencies.

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